Searching evidences of new physics in the light of the $\mu\nu$SSM

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Together..........

PG, Daniel E. López-Fogliani, Vasiliki A. Mitsou,
Carlos Muñoz and Roberto Ruiz de Austri

⋆ arXiv:1403.3675 [hep-ph] ⋆
Hunting physics beyond the standard model with unusual $W^{\pm}$ and Z decay

⋆ Phys. Rev. D 88, 015009 (2013), arXiv:1211.3177 [hep-ph] ⋆
Probing the μ-from-ν supersymmetric standard model with displaced multileptons from the decay of a Higgs boson at the LHC

PG, David G. Cerdeño, Chan Beom Park

⋆ JHEP 1306 (2013) 031, arXiv:1301.1325 [hep-ph] ⋆
Probing the two light Higgs scenario in the NMSSM with a low-mass pseudoscalar

The Standard Model, The LHC and us .....

- No excess confirmed over the SM predictions

- And..... A scalar at the LHC.. PLB716 (2012) 1,30 appears to be 0^+.. with mass about 125 GeV.. $\mu = 1.30 \pm 0.12\ (\text{stat})^{+0.14}_{-0.11}\ (\text{sys})$.. ATLAS-CONF-2014-009, PLB726 (2013) 120, 1312.5353...

Is this the one.... ?

⋆ $\Gamma_{\text{Higgs}} < 4.2 \times \Gamma^{\text{SM}}_{\text{Higgs}}$.... CMS-PAS-HIG-14-002 ⋆ Br (Higgs $\longrightarrow$ invisible) < 0.58@ 95 % C.L. .... 1404.1344 [hep-ex]...

⋆ Apparent excess in $\gamma\gamma$ still for ATLAS.. (1.57).. ATLAS-CONF-2014-009.. Now also in the CMS... (1.13)... ⋆ Need precise measurement of $b\bar{b}$..

Hope survives....

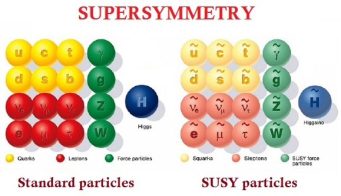
⋆ LHC@14 TeV... $\mathcal{L} \sim 3000\ fb^{-1}$ ⋆ Golden future... ILC.. CLIC.. TLEP

But... Neutrino mass..?, Dark Matter..? ....

New Physics is much needed..... Supersymmetry.. Scalar mass in protected..

Beyond the SM with SUSY

Need two Higgs doublets.. H_u, H_d



- Cure to gauge hierarchy problem of the SM with superpartners....
- Stable lightest SUSY particle $\Longrightarrow$ DM candidate
- Enhanced FV $\Longrightarrow$ stringent constraint
- gauge coupling unification

However, a class of issues to be addressed... e.g... μ-problem.. massive neutrinos.. $\longrightarrow$ a handful of models... larger parameter set.. less predictive.. ...

Is there an economic way...... ?

Introducing $\mu\nu$SSM López-Fogliani, Muñoz

NMSSM

$\lambda \hat{S} \hat{H}_d^a \hat{H}_u^b \Longrightarrow \mu_{eff} = \lambda v_s$

MSSM + RH-neutrinos or ....$\not{R}_P$ $\Longrightarrow$
MSSM + $\epsilon^i \hat{L}_i^a \hat{H}_u^b$ (one m_ν at the tree-level.. loop corrections are essential) and/or $\frac{1}{2}\lambda_{ijk} \hat{L}_i^a \hat{L}_j^b \hat{e}_k^c$ and/or $\lambda'_{ijk} \hat{L}_i^a \hat{Q}_j^b \hat{d}_k^c$ (m_ν through loops)

NMSSM

$\cancel{\lambda \hat{S} \hat{H}_d^a \hat{H}_u^b}$

ϵ-problem... Nilles, Polonsky, NPB 484, 33 (1997)
Loop corrections are essential.. Many parameters.. Less predictive.... Trilinear $\cancel{R}_P$.. Critically challenged with LFV..... Dreiner, Nickel, Staub, Vicente, PRD 86,015003 (2012)

Introducing $\mu\nu$SSM López-Fogliani, Muñoz

It is... $\overbrace{\lambda^i \hat{\nu}^c_i \hat{H}^a_d \hat{H}^b_u}^{R_p\!\!\!/ \text{ with } \Delta L=1}$

★ **Natural entry of $Y^{ij}_\nu \hat{H}^b_u \hat{L}^a_i \hat{\nu}^c_j$**

$$W = \underbrace{\epsilon_{ab}(Y^{ij}_u \hat{H}^b_u \hat{Q}^a_i \hat{u}^c_j + Y^{ij}_d \hat{H}^a_d \hat{Q}^b_i \hat{d}^c_j + Y^{ij}_e \hat{H}^a_d \hat{L}^b_i \hat{e}^c_j)}_{W^{MSSM} - \epsilon_{ab}\mu \hat{H}^a_d \hat{H}^b_u} +$$

$$\epsilon_{ab}\ \underbrace{(Y^{ij}_\nu \hat{H}^b_u \hat{L}^a_i \hat{\nu}^c_j}_{\epsilon^i_{eff} = Y^{ij}_\nu \langle \tilde{\nu}^c_j \rangle} - \underbrace{\overbrace{\lambda^i \hat{\nu}^c_i \hat{H}^a_d \hat{H}^b_u)}^{R_p\!\!\!/ \text{ with } \Delta L=1}}_{\mu_{eff} = \lambda^i \langle \tilde{\nu}^c_i \rangle} + \underbrace{\overbrace{\frac{1}{3}\kappa^{ijk} \hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c_k}^{R_p\!\!\!/ \text{ with } \Delta L=3}}_{m_{\nu^c_{ij}} = 2\ \kappa^{ijk} \langle \tilde{\nu}^c_k \rangle}$$

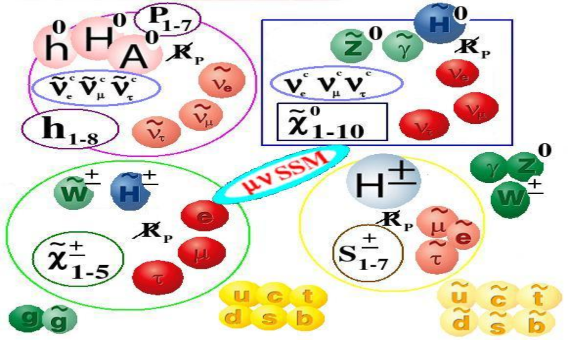
López-Fogliani, Muñoz, PRL 97, 041801 (2006)

$Y^{ij}_\nu \hat{H}^b_u \hat{L}^a_i \hat{\nu}^c_j$ **is the seed of $R_p\!\!\!/$.... with $Y_\nu \rightarrow 0$....** $\hat{\nu}^c \Leftrightarrow \hat{S}... \Rightarrow R_p\!\!\!/$

TeV scale seesaw with right-handed neutrino + $R_p\!\!\!/ \implies m_\nu \neq 0$

PG, Roy *JHEP* 04 (2009) 069; Fidalgo, López-Fogliani, Muñoz and Ruiz de Austri *JHEP* 08 (2009) 105; PG, Dey, Mukhopadhyaya and Roy *JHEP* 05 (2010) 087

Introducing $\mu\nu$SSM López-Fogliani, Muñoz

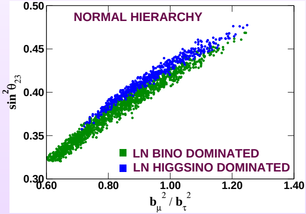


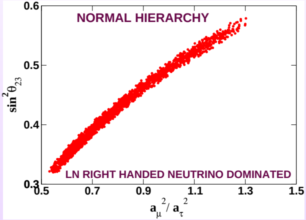
Significance of Lepton number (L) is lost

- MSSM + $R\!\!\!/_P$ + 3 $\hat{\nu}_i^c$ $\Longrightarrow$ 8(7) CP-even(odd) states $h_\alpha(P_\alpha)$ / 10 neutralinos $\widetilde{\chi}^0_\alpha$ / 7 charged states $S^\pm_\alpha$ / 5 charginos $\widetilde{\chi}^\pm_\alpha$

The neutrinos in the $\mu\nu$SSM

$3\ \hat{\nu}^c + Y_\nu^{ii} \Longrightarrow$ **correct neutrino physics at the tree level** PG, Roy *JHEP* 2009

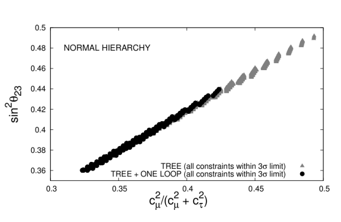


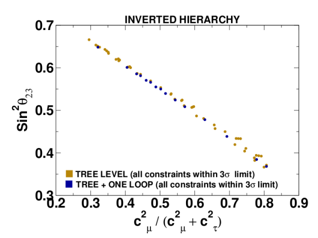


$$a_i = Y_\nu^{ii} v_u,\ b_i = a_i \cot\beta + 3\lambda c_i,\ c_i = \nu_i$$

The neutrinos in the $\mu\nu$SSM

Loop corrections are important.. depend on mass hierarchy.. PG, Dey, Mukhopadhyaya, Roy, JHEP 05 (2010) 087

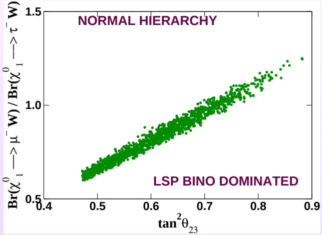


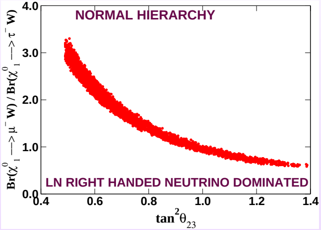


$$a_i = Y_\nu^{ii} v_u, b_i = a_i \cot\beta + 3\lambda c_i, c_i = \nu_i$$

Goliath meets David.....

Correlations between neutrino mixing angles and LSP decay.. PG, Roy *JHEP* 2009



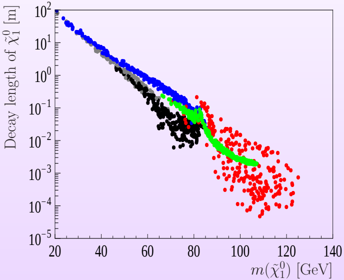


Also by Bartl, Hirsch, Vicente, Liebler, Porod, JHEP 05, 120 (2009)

Mukhopadhyaya, Roy, Vissani,PLB 443, 191 (1998)
Choi, Chun, Kang, Lee, PRD 60, 075002 (1999)
Romao, Diaz, Hirsch, Porod, Valle, PRD 61, 071703 (2000)

Novel signals with the $\mu\nu$SSM....... The proposal ...

- **Low mass ($\lesssim m_W$) unstable LSP ($\tilde{\chi}^0$) decays mainly through $\ell^\pm W^{\mp *}$, νZ^* while $l_{DL} \sim 1/m^4_{\chi^0}$...**
- **When $m_{\chi^0} < 20$ GeV... $l_{DL} > 100$ m**
- **$d_{\rm ATLAS} \sim 25$ m $\Longrightarrow$ light $\tilde{\chi}^0$ ($\lesssim 40$ GeV)... $R\!\!\!/_P$ is an impostor to $R_p C$**



Bartl, Hirsch, Vicente, Liebler, Porod, JHEP 0905, 120

- **Low mass ($\lesssim m_W$) unstable LSP ($\widetilde{\chi}^0$) decays mainly through $\ell^{\pm} W^{\mp *}$, νZ^* while** $l_{DL} \sim 1/m^4_{\chi^0}$...
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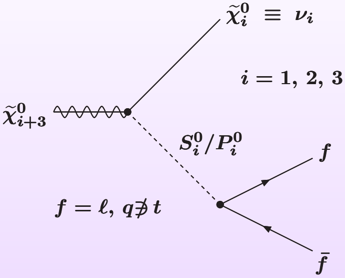


PG *et al.* to appear in arXiv

A light $\widetilde{\chi}^0$ through $\widetilde{\chi}^0 \to h_i/P_i + \nu^i_L$ can yield mesoscopic DV ($1\ cm \lesssim l_{DL} \lesssim 3\ m$)

Also possible in trilinear $\not{R}_P$ for certain range of couplings.. see see hep-ph/0406039

Light h_i, P_i are possible in the $\mu\nu$SSM... A very light $\widetilde{\chi}^0$ ($\lesssim 20$ GeV) is detectable!..

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, PRD 88, 015009 (2013)

How about $Z \to \widetilde{\chi}^0\widetilde{\chi}^0$, h_iP_j, $W^{\pm} \to \widetilde{\chi}^0\widetilde{\chi}^{\pm}_{1,2,3}$ at colliders....?

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, arXiv:1403.3675 [hep-ph]

And finally Higgs$\to \widetilde{\chi}^0\widetilde{\chi}^0$ at the LHC and further...

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, PRD 88, 015009 (2013)

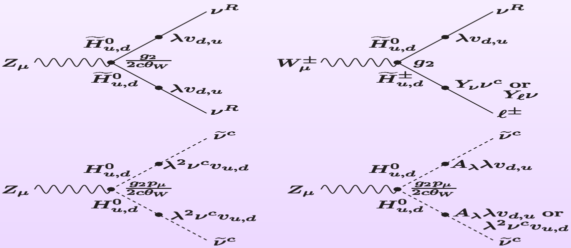
Setting up the convention... the signals

- **Small** κ, A_κ, λ_i $\Longrightarrow$ **light singlet-like** h_i, P_i, $\widetilde{\chi}^0_{i+3}$ $(i = 1, 2, 3)$

  Formulas are coming.... PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, to appear in arXiv

- h_4 **is the lightest doublet-like Higgs while** $\widetilde{\chi}^0_4$ **is the lightest neutralino**

  Fidalgo, López-Fogliani, Muñoz, Ruiz de Austri JHEP 1110, 020 (2011)



Prompt + Displaced yet detectable multi-leptons/jets/photons at the LHC

$$Z \longrightarrow \widetilde{\chi}^0_4 \widetilde{\chi}^0_4 \longrightarrow 2h_i/P_i + 2\nu \longrightarrow 2\ell^+_D \ell^-_D \,/ 2q_D\bar{q}_D + 2\nu$$

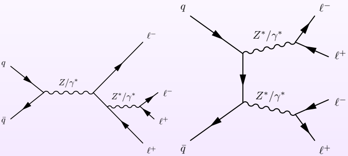
$$Z \longrightarrow h_i P_j \longrightarrow 2\ell^+_P \ell^-_P\,,\ \ell^+_P \ell^-_P\, q_P \bar{q}_P \text{...etc..}$$

$$W^\pm \longrightarrow \widetilde{\chi}^0_4 \widetilde{\chi}^\pm_{1,2,3} \longrightarrow \ell^+_D \ell^-_D \,/ q_D \bar{q}_D + \nu + \ell^\pm_P$$

τ or b-jet rich signals

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, arXiv:1403.3675 [hep-ph]

The $W^{\pm}$ and Z decays... a broader perspective



SM-Br($Z \to 4\ell,\ 4b$) $\lesssim 4.2^{+0.9}_{-0.8} \times 10^{-6}, 3.6^{+1.3}_{-1.3} \times 10^{-4}$
PDG, PRD 86, 010001 (2012)

Latest LHC reporting... only e, μ

CERN-CMS-NOTE-2006-057; JHEP 12, 034 (2012);
ATLAS-CONF-2013-055; PRL 112, 231806 (2014)

e, μ, τ, jets....

$*$ **MSSM + b$R\!\!\!/_P$.. decays outside detector for $m_{\tilde{\chi}^0} < 20$ GeV... DISPLACED $W^{\pm}$, Z**

$*$ **MSSM + t$R\!\!\!/_P$.. decays between 1 cm − 3 m for $m_{\tilde{\chi}^0} < 20$ GeV with $\lambda_{ijk} \sim \mathcal{O}(10^{-3})$...**
hep-ph/0406039 **DISPLACED $W^{\pm}$, Z.. often with slightly altered topology..e.g., $2\ell_P 2\ell_D + \not{E}_T$**

Rich in τ, b − jets....

$*$ **NMSSM.. DISPLACED decays for $Z \to$ bino-like NLSP pair $\to$ 2 LSP + 2 $h/P \to 2\ell^+\ell^-/q\bar{q} + \not{E}_T$**

PROMPT Z decays {SM backgrounds}... $Z \to h + P \to 2\ell^+\ell^-/q\bar{q}$.. Nothing for $W^{\pm}$

$*$ **NMSSM + $3\hat{\nu}^c$.. DISPLACED & PROMPT decays for $Z \to 2\ell^+\ell^-/q\bar{q}$.... $R\!\!\!/_P$ and R_pC.. DISPLACED decays for $W^{\pm}$** ..... Kitano, Oda, PRD 61, 113001 (2000)

$*$ **The $\mu\nu$SSM.. *minimal extension* beyond the MSSM $\Longrightarrow$ distinctive collider signatures + correct neutrino physics**

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, arXiv:1403.3675 [hep-ph]

Probing new $W^{\pm}$ and Z decays....

Challenges... $\tau/\mathrm{b}-\mathrm{jet}$ rich signal.... Detection of soft, collimated and often displaced objects.... Need better statistics... better detection

$*$ Br($Z \longrightarrow 2x_D 2y_D + \not{E}_T$) or Br($Z \longrightarrow 2x_P 2y_P + \not{E}_T$) $\sim \mathcal{O}(10^{-5})$ or less.. $x, y = \ell, q, \gamma$

$*$ May remain hidden within SM process..for $x = b$... Br($Z \longrightarrow b\bar{b}b\bar{b}$) $\lesssim 3.6^{+1.3}_{-1.3} \times 10^{-4}$

$*$ e.g. 2ℓ and 4ℓ mass peaks may get lost in the SM continuum.. see PRL 112, 231806 (2014)

$*$ Detectable at the LHC... novel future.. GigaZ (linear collider) and TeraZ (TLEP) mode

$*$ 2×10^9 (GigaZ).. 7×10^{11} (TeraZ) Z events/year $\Longrightarrow$ sensitive to much lower Br

hep-ph/0102083; hep-ex/0106057; JHEP 01, 164 (2014)

$*$ Br($W^{\pm} \longrightarrow x_D y_D + \not{E}_T + \ell^{\pm}_P$) $\sim \mathcal{O}(10^{-13})$ or less..

$*$ Difficult at the LHC... also in future.. MegaW (linear collider) and OkuW (TLEP) mode

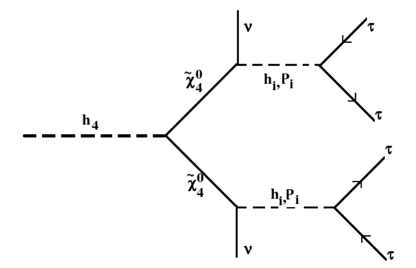
$*$ 2×10^6 (MegaW).. 7×10^8 (OkuW) $W^{\pm}$ events/year $\Longrightarrow$ need much lower sensitivity.. ☹

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, arXiv:1403.3675 [hep-ph]

Hope... techniques from flavour observables... ☺

LHCb Br($B_s^0 \longrightarrow \mu^+\mu^-$) $\sim \mathcal{O}(10^{-10})$ sensitive to η.... work in progress..

The signals...contd.. back with Higgs



Masses	Values in GeV
m_{h_4}	125.7
$m_{P_1}, m_{P_2}, m_{P_3}$	3.6, 3.8, 5.5
$m_{h_1}, m_{h_2}, m_{h_3}$	7.5, 8.0, 19.6
$m_{\tilde{\chi}_4^0}, m_{\tilde{\chi}_5^0}, m_{\tilde{\chi}_6^0}$	9.6, 11.5, 11.9

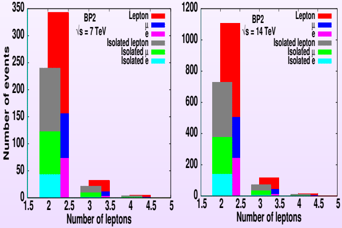
Displaced yet detectable multi-leptons/jets/photons at the LHC

$$gg \longrightarrow h_4 \longrightarrow \tilde{\chi}_4^0 \tilde{\chi}_4^0 \longrightarrow 2h_i/P_i + 2\nu \longrightarrow 2\tau_D^+ 2\tau_D^- 2\nu$$

Prompt multi-leptons/jets/photons or mixed states are also possible from Higgs to Higgs cascades... $h_4 \longrightarrow h_i h_j, P_i P_j$... like the NMSSM

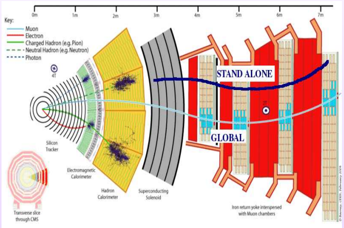
Cerdeño, PG, Park, JHEP 1306 (2013) 031

A little price to pay....



Bandyopadhyay, PG, Roy, PRD84, 115022 (2011)

Stand-alone muons...



- **Final state n_ℓ is independent of $Y_{\nu_{ij}}$ and ν_i.. ☺**

To kill the backgrounds......Higgs

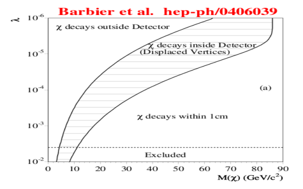
Mesoscopic displaced vertex....
Displaced charge tracks....

Irreducible impostor NMSSM $+ 3\hat{\nu}^c$..
Kitano, Oda, PRD 61, 113001 (2000)

- **All SM (e.g. ZZ^*)/SUSY backgrounds ($e.g.\ h_1 \to P_1 P_1 \to 2\ell^+ 2\ell^-$@NMSSM), with prompt ℓ are effaced ... also long-lived b/c meson decays**
- **NMSSM with $10^{-3} \lesssim \lambda \lesssim 10^{-2}$... light NLSP $\to$ LSP $+ h/P$, with $h/P \to \ell^+\ell^- \Rrightarrow$ a possible impostor..** Ellwanger, Hugonie, Eur. Phys. J. C 5, 723 (1998); Eur. Phys. J. C 13, 681 (2000)
- **NLSP $\to$ LSP $+ h/P$, never produces mesoscopic decay length....** Eur. Phys. J. C 13, 681 (2000)

- **Options.. e.g. MSSM $+\frac{1}{2}\lambda^{ijk}\hat{L}_i\hat{L}_j\hat{E}^c_k$.. difficult with, LEP (and LHC) results... but not impossible**

Dreiner, Kim, Lebedev, PLB 715, 199 (2012)



To kill the backgrounds......Higgs

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Irreducible impostor NMSSM $+ 3\hat{\nu}^c$**..**
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- **All SM (e.g.** ZZ^***)/SUSY backgrounds** ($e.g.$ $h_1 \to P_1 P_1 \to 2\ell^+ 2\ell^-$ @NMSSM)**, with prompt** ℓ **are effaced ... also long-lived** b/c **meson decays**
- **NMSSM with** $10^{-3} \lesssim \lambda \lesssim 10^{-2}$**... light NLSP** $\to$ **LSP** $+ h/P$**, with** $h/P \to \ell^+\ell^-$ $\Rrightarrow$ **a possible impostor..** Ellwanger, Hugonie, Eur. Phys. J. C 5, 723 (1998); Eur. Phys. J. C 13, 681 (2000)
- **NLSP** $\to$ **LSP** $+ h/P$**, never produces mesoscopic decay length....** Eur. Phys. J. C 13, 681 (2000)

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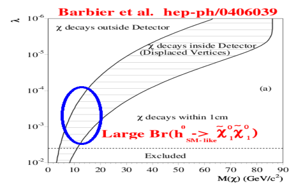
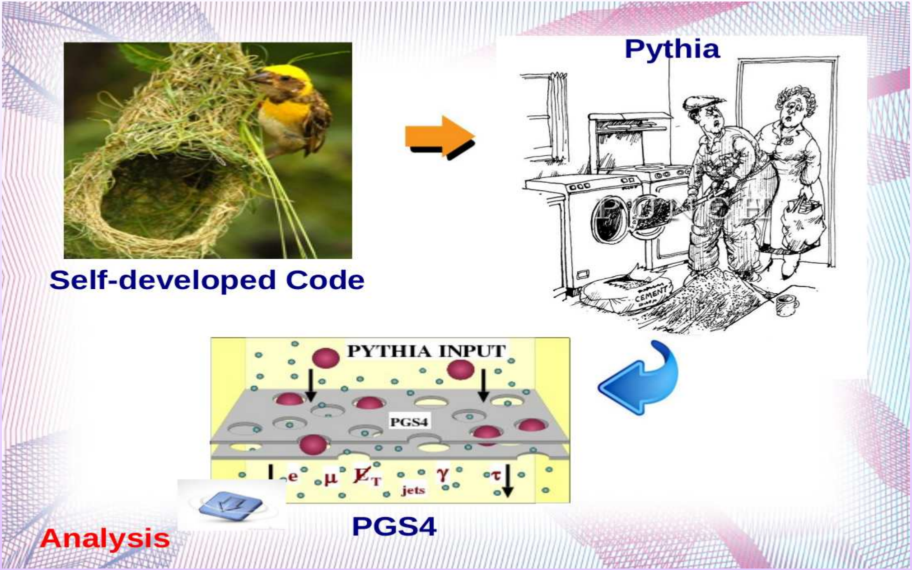
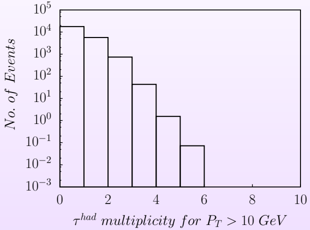


Following the footsteps.....



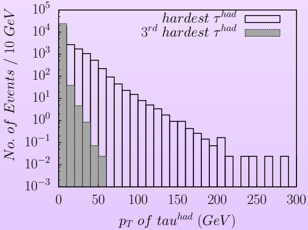
$\tau_{\rm had}$ multiplicity



- $4\tau^{\rm had} \sim 18\%$... $\tau \to \tau_{\rm had} \sim 65\%$
- **Highly collimated QCD jets faking $\tau^{\rm had}$..... $\Longrightarrow$ $n^{\tau^{\rm had}} > 4$... disappears with higher $p_{\rm T}^{\tau^{\rm had}}$ cut**

- **$\tau^{\rm had}$'s are clearly the best bet... next one is of course μ......** careful about PLB 726 (2013) 564

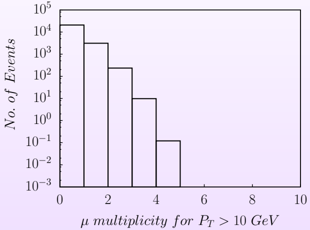
$p_{\rm T}^{\tau_{\rm had}}$ distribution for 1^{st} and 3^{rd} leading $\tau_{\rm had}$



PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, PRD 88, 015009 (2013)

μ multiplicity... @8 TeV @20 fb^{-1}

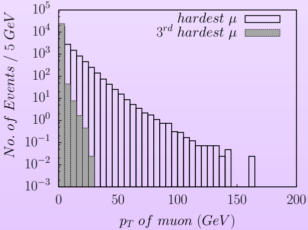
μ multiplicity



- $4e, 4\mu$s from $\tau \sim 0.1\%$.... $\tau \to \tau_{\rm lep} \sim 35\%$
- e, μs are from leptonic τ decay.. although $h_i/P_i \to \mu^+\mu^-$ is possible

- $\tau^{\rm had}$'s are clearly the best bet... next one is of course μ...... careful about PLB 726 (2013) 564

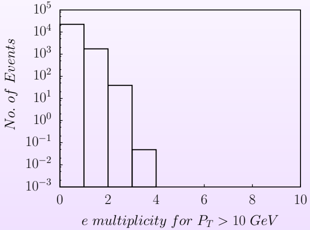
p_T^μ distribution for 1st and 3rd leading μ



PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, PRD 88, 015009 (2013)

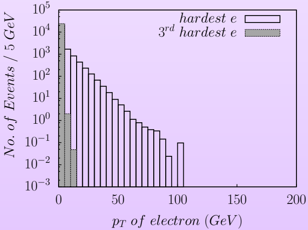
e multiplicity... @8 TeV @20 fb^{-1}

e multiplicity



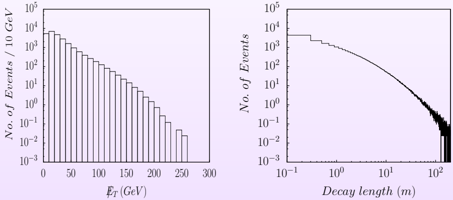
- **Life with es seems really hard.. ☹**

p_{T}^{e} distribution for 1^{st} and 3^{rd} leading e



PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, PRD 88, 015009 (2013)

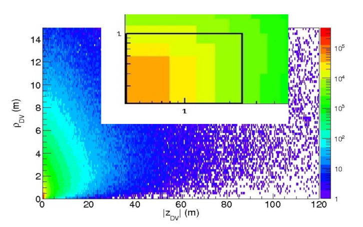
$\not{E}_T$ and DL distribution



- Moderately high $MET \Lleftarrow \quad \gtrsim 6$ neutrinos from $\widetilde{\chi}_4^0$ and τ decays...
- $c\tau_{\widetilde{\chi}_4^0} \approx 30$ cm.... large number of events appear inside charge tracker

$|z_{\rm DV}|$ vs $\rho_{\rm DV}$

- A large fraction of DVs appear within $|z_{\rm DV}| \lesssim 2.5$ m and $\rho_{\rm DV} \lesssim 1$ m, i.e, in the range of inner tracker



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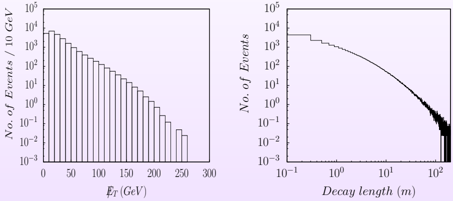

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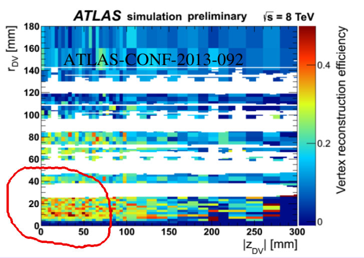
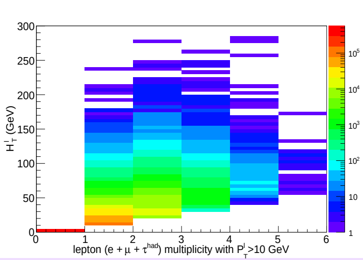


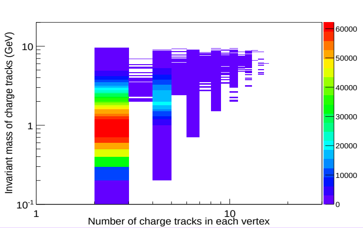
ATLAS-CONF-2013-092

- $H_{\rm T}^{\ell}$ is moderately high for larger lepton multiplicity
- $H_{\rm T}^{\ell} + \not{E}_T$ can be used as a differentiator

$H_{\rm T}^{\ell}$ ($\equiv \sum p_{\rm T}^{\ell}$) distribution



Charge track mass vs n_{trk}



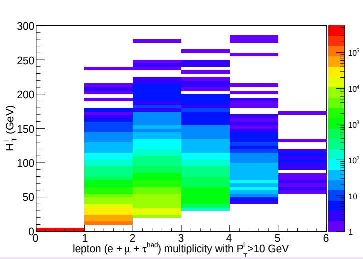
$n_{trk}^{vertex}|_{max} = 12$, **four 3-prong τ decay**

- A very useful event selection criteria
- ☹ Sensitive for $n_{trk} > 4$ and vertex mass > 10 GeV... G. Aad *et al.* [ATLAS] 2013
- Room for development... sensitivity to low vertex mass
- Life is better with jets

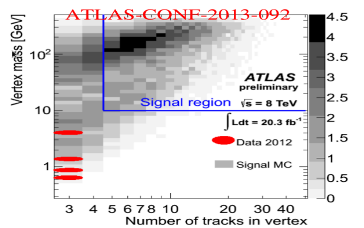
Probing DVs

- H_T^ℓ is moderately high for larger lepton multiplicity
- $H_T^\ell + \not{E}_T$ can be used as a differentiator

H_T^ℓ ($\equiv \sum p_T^\ell$) distribution



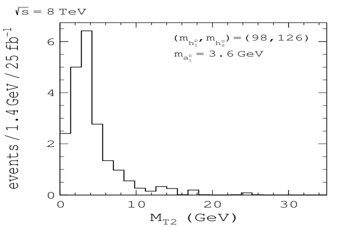
Charge track mass vs n_{trk}



Need higher vertex mass and larger # of tracks.. jets???

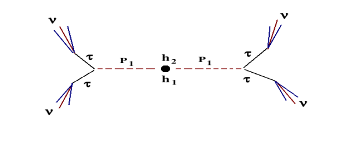
- A very useful event selection criteria
- ☹ Sensitive for $n_{trk} > 4$ and vertex mass > 10 GeV... G. Aad *et al.* [ATLAS] 2013
- Room for development... sensitivity to low vertex mass
- Life is better with jets

M_{T2} distribution



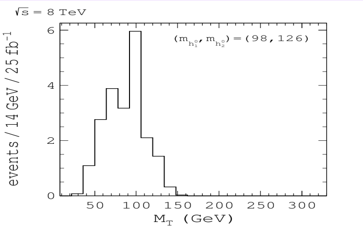
- Signals $h_2,\ h_1 \to P_1 P_1 \to 2\tau^+ 2\tau^-$
- τ rich signal... better detection efficiency than $2m_\tau \lesssim m_{P_1} \lesssim 2m_b$
- Also considered $2m_{h_1} \lesssim m_{h_2}$... experimentally more challenging.. softer τs from $h_1 \to P_1 P_1$ decays

Need small $\Delta_{\ell^+\ell^-}$



- Good estimation of the mass scale...

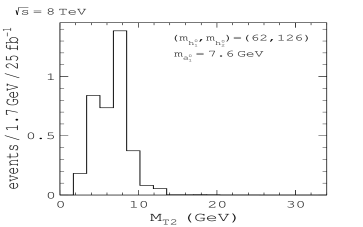
M_T distribution



Cerdeño, PG, Park, JHEP 1306 (2013) 031

$2m_{h_1} \lesssim$ 126+126 GeV Higgses with light P_1 @ NMSSM

M_{T2} distribution



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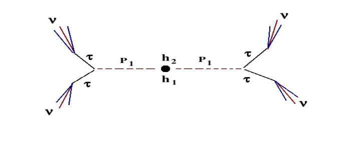
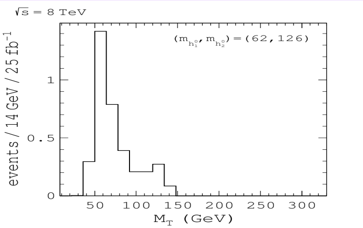


- **Good estimation of the mass scale...**

M_{T} distribution



Cerdeño, PG, Park, JHEP 1306 (2013) 031

Summary and conclusion...... and beyond

• Light singlet-sector can produce novel and/or indirect (decays of heavier SM particles) evidence of new physics $\Longrightarrow$ need experimental attention

• $\mu\nu$SSM.... least extension beyond the MSSM to solve the μ-problem and reproduce correct neutrino physics

• Novel signals are well expected with enriched mass spectrum and broken R_p

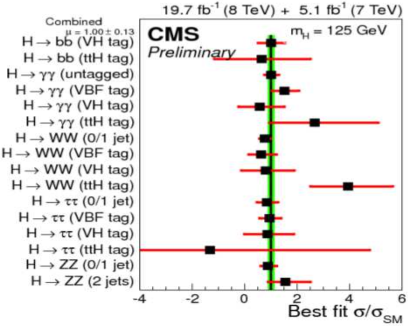
• Displaced and/or soft objects at the LHC $\Rightarrow$ lesser backgrounds.. new signs are well envisaged but with sophisticated collider analyses of soft and/or displaced objects

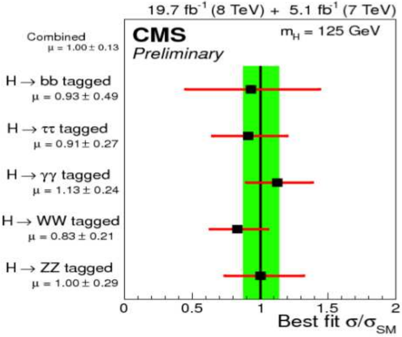
• Unique SUSY signatures are also possible

With new data and up-gradation to 14 TeV and beyond...... more phenomenological wonder with $\mu\nu$SSM are awaiting.....

Dreaming the future..

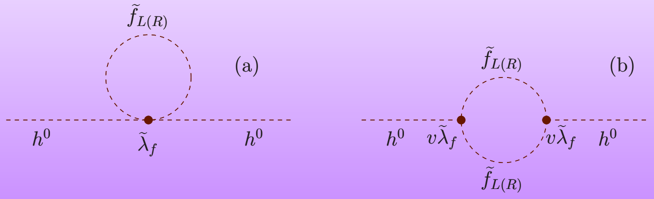
h signal strength at best fit mass





- $\mu = 1.00 \pm 0.13$

Loop corrections in SUSY



New one-loop radiative corrections to Higgs boson in SUSY

- **Certain restrictions on masses and couplings of new states $\Longrightarrow$ radiative correction vanishes**
- **Symmetry between states of different spin quantum numbers $\Longrightarrow$ Higgs (scalar) mass is protected**

μ-problem

- **MSSM superpotential**

$$W = \epsilon_{ab}(Y_u^{ij}\hat{H}_u^b\hat{Q}_i^a\hat{u}_j^c + Y_d^{ij}\hat{H}_d^a\hat{Q}_i^b\hat{d}_j^c + Y_e^{ij}\hat{H}_d^a\hat{L}_i^b\hat{e}_j^c) - \underline{\epsilon_{ab}\mu\hat{H}_d^a\hat{H}_u^b}$$

- **Since μ ϵ superpotential $\longrightarrow$ μ respects supersymmetry (SUSY)**
- **μ appears in the EWSB, generates TeV-scale higgsino masses**
- **SUSY respecting $\mu \sim$ SUSY breaking TeV-scale soft terms $\Longrightarrow$ μ-problem**

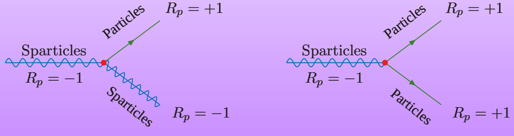
J. E. Kim and H. P. Nilles, Phys. Lett. B 138, 150 (1984)

- **Alternatively,**

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2\tan^2\beta}{\tan^2\beta - 1} - |\mu^2|.$$

R-Parity

- R_p, a discrete symmetry $\Longrightarrow$ prevents too fast proton decay through sparticle mediated process
- $R_p = (-1)^{L+3B+2S}$ with $L(B)$ as lepton(baryon) and S as spin



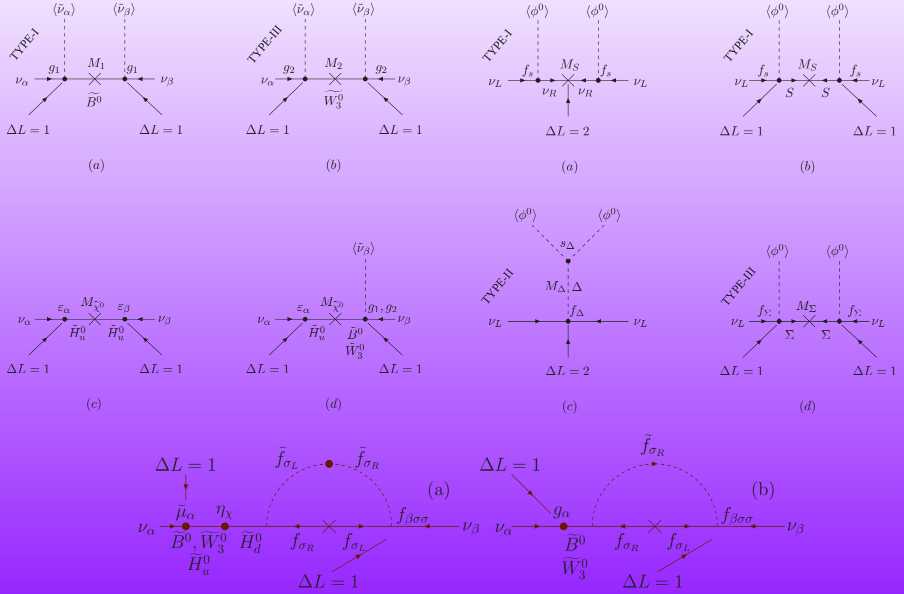
R_p **conserved** $\quad$ R_p **violated**

- R_p conservation $\Longrightarrow$ stable Lightest Supersymmetric Particle (LSP)
- Most general MSSM superpotential with bilinear and trilinear $\not{R}_P$

$$W = \epsilon_{ab}(Y_u^{ij}\hat{H}_u^b\hat{Q}_i^a\hat{u}_j^c + Y_d^{ij}\hat{H}_d^a\hat{Q}_i^b\hat{d}_j^c + Y_e^{ij}\hat{H}_d^a\hat{L}_i^b\hat{e}_j^c - \mu\hat{H}_d^a\hat{H}_u^b)$$

$$-\epsilon_{ab}(\underbrace{\epsilon^i\hat{L}_i^a\hat{H}_u^b}_{\Delta L=1,\Delta B=0} + \overbrace{\frac{1}{2}\lambda^{ijk}\hat{L}_i^a\hat{L}_j^b\hat{e}_k^c}^{\Delta L=1,\Delta B=0} + \underbrace{\lambda'^{ijk}\hat{L}_i^a\hat{Q}_j^b\hat{d}_k^c)}_{\Delta L=1\Delta B=0,} + \overbrace{\lambda''^{ijk}\hat{u}_i^c\hat{d}_j^c\hat{d}_k^c}^{\Delta L=0,\Delta B=1}$$

$m_\nu \neq 0$


TYPE-I
TYPE-III
TYPE-I
TYPE-I
TYPE-II
TYPE-III
$\langle\tilde{\nu}_\alpha\rangle$ $\langle\tilde{\nu}_\beta\rangle$
ν_α g_1 M_1 g_1 ν_β $\widetilde{B}^0$
ν_α g_2 M_2 g_2 ν_β $\widetilde{W}_3^0$
ν_α ε_α $M_{\tilde{\chi}^0}$ ε_β ν_β $\tilde{H}_u^0$ $\tilde{H}_u^0$
ν_α ε_α $M_{\tilde{\chi}^0}$ g_1, g_2 ν_β $\tilde{H}_u^0$ $\tilde{B}^0$ $\tilde{W}_3^0$
$\langle\phi^0\rangle$
ν_L f_s M_S f_s ν_L ν_R ν_R
ν_L f_s M_S f_s ν_L S S
s_Δ M_Δ Δ f_Δ ν_L ν_L
ν_L f_Σ M_Σ f_Σ ν_L Σ Σ
$\Delta L = 1$
$\Delta L = 2$
(a) (b) (c) (d)
ν_α $\widetilde{\mu}_\alpha$ η_χ $\widetilde{B}^0, \widetilde{W}_3^0$ $\widetilde{H}_u^0$ $\widetilde{H}_d^0$ $\widetilde{f}_{\sigma_L}$ $\widetilde{f}_{\sigma_R}$ f_{σ_R} f_{σ_L} $f_{\beta\sigma\sigma}$ ν_β
(a)
ν_α g_α $\widetilde{B}^0$ $\widetilde{W}_3^0$ $\widetilde{f}_{\sigma_R}$ f_{σ_R} f_{σ_L} $f_{\beta\sigma\sigma}$ ν_β
(b)

The soft terms

- **The Lagrangian $\mathcal{L}_{\text{soft}}$, containing the soft-supersymmetry-breaking terms is given by**

$$-\mathcal{L}_{\text{soft}} = (m^2_{\tilde{Q}})^{ij} \tilde{Q}^{a^*}_i \tilde{Q}^a_j + (m^2_{\tilde{u}^c})^{ij} \tilde{u}^{c^*}_i \tilde{u}^c_j + (m^2_{\tilde{d}^c})^{ij} \tilde{d}^{c^*}_i \tilde{d}^c_j + (m^2_{\tilde{L}})^{ij} \tilde{L}^{a^*}_i \tilde{L}^a_j$$
$$+ (m^2_{\tilde{e}^c})^{ij} \tilde{e}^{c^*}_i \tilde{e}^c_j + m^2_{H_d} H^{a^*}_d H^a_d + m^2_{H_u} H^{a^*}_u H^a_u + (m^2_{\tilde{\nu}^c})^{ij} \tilde{\nu}^{c^*}_i \tilde{\nu}^c_j$$
$$+ \epsilon_{ab} \left[(A_u Y_u)^{ij} H^b_u \tilde{Q}^a_i \tilde{u}^c_j + (A_d Y_d)^{ij} H^a_d \tilde{Q}^b_i \tilde{d}^c_j + (A_e Y_e)^{ij} H^a_d \tilde{L}^b_i \tilde{e}^c_j + \text{H.c.} \right]$$
$$+ \left[\epsilon_{ab} (A_\nu Y_\nu)^{ij} H^b_u \tilde{L}^a_i \tilde{\nu}^c_j - \epsilon_{ab} (A_\lambda \lambda)^i \tilde{\nu}^c_i H^a_d H^b_u + \frac{1}{3} (A_\kappa \kappa)^{ijk} \tilde{\nu}^c_i \tilde{\nu}^c_j \tilde{\nu}^c_k + \text{H.c.} \right]$$

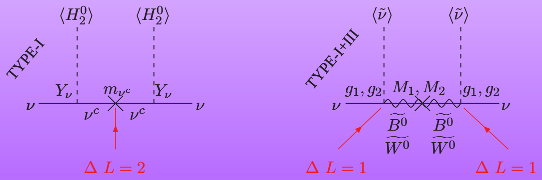
- **The neutral fields develop non zero VEVs while minimizing the neutral scalar potential,**

$$\langle H^0_d \rangle = v_d \,, \quad \langle H^0_u \rangle = v_u \,, \quad \langle \tilde{\nu}_i \rangle = \nu_i \,, \quad \langle \tilde{\nu}^c_i \rangle = \nu^c_i \,.$$

Neutrino mass generation in $\mu\nu$SSM

"TeV - scale" Type I + Type III seesaw, even with flavour diagonal neutrino Yukawa couplings $\Longrightarrow$ tree level masses for all three neutrinos

PG and Roy, JHEP 04, 069 (2009)



$m_\nu \sim \frac{Y_\nu^2 \langle H_u^0\rangle^2}{m_{\nu^c}}$ **TYPE-I**

$m_\nu \sim \frac{g^2 \langle\tilde{\nu}\rangle^2}{m_{\chi^0}}, \quad m_{\chi^0} = M_1, M_2$ **TYPE-I+III**

- Approximate analytical expression for entries of M^{tree}_{seesaw} matrix

$$(M^{tree}_{seesaw})_{ij} \approx \frac{a_i a_j}{6\kappa\nu^c}(1 - 3\delta ij) - \frac{1}{2M_{eff}}\left[c_i c_j + \frac{(a_i c_j + a_j c_i)}{3\lambda tan\beta} + \frac{a_i a_j}{9\lambda^2 tan^2\beta}\right]$$

PG and Roy, JHEP 04, 069 (2009)

where $$M_{eff} = \left[1 - \frac{v^2}{2M(\kappa{\nu^c}^2 + \lambda v_d v_u)\mu}\left(\kappa{\nu^c}^2 \sin 2\beta + \frac{\lambda v^2}{2}\right)\right], \frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}$$

$$v^2 = v_d^2 + v_u^2, \ tan\beta = \frac{v_u}{v_d}, \ a_i = Y_\nu^{ii} v_u, \ c_i = \nu_i, \ i = e, \mu, \tau$$

- In the limit $\nu^c \to \infty$ and $v \to 0$, equation one reduces to

$(M^{tree}_{seesaw})_{ij} \approx -\frac{c_i c_j}{2M} \Longrightarrow$ **Gaugino seesaw or Type - III seesaw**

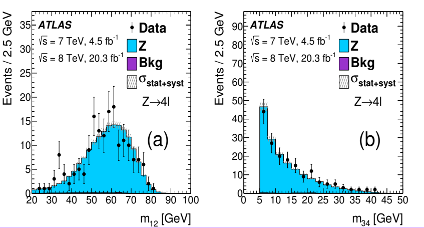
- In the limit $M \to \infty$, same equation reduces to

$(M^{tree}_{seesaw})_{ij} \approx \frac{a_i a_j}{6\kappa\nu^c}(1 - 3\delta ij) \Longrightarrow$ **Ordinary seesaw or Type - I seesaw.**

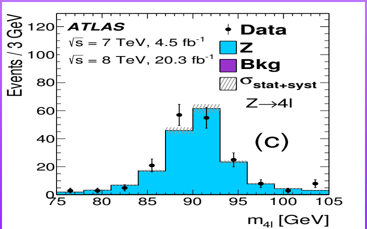
$Z \longrightarrow 4\ell$, $\ell = e, \mu$ in ATLAS

- $E_{\rm CM} = 8$ TeV, $\mathcal{L} = 20.3\ {\rm fb}^{-1}$, Br$(Z \longrightarrow 4b) \sim 10^{-5} \Longrightarrow \sigma(pp \longrightarrow Z \longrightarrow 4b) \times \mathcal{L} \approx 5150$ events.. without any kinematical cuts
- In the SM ≈ 185400 events with Br$(Z \longrightarrow 4b) \sim 3.6 \times 10^{-4}$!!!!!!

2ℓ m_{inv} distributions



4ℓ m_{inv} distribution



- Poor detection efficiency for low $p_{\rm T}$ τs compared to e, μ....